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VERTICAL CAVITY SURFACE EMITTING SEMICONDUCTOR LASER WITH TRIANGLE PRISM OPTICAL CAVITY RESONATOR

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

The invention relates to light generation devices and, more particularly, to a vertical cavity surface emitting semiconductor laser (VCSEL) with a triangle prism optical cavity resonator.

2. DESCRIPTION OF THE RELATED ART

Light generation devices such as semiconductor laser diodes having optical cavities for light generation are commonly known and have been implemented in numerous applications in the art. However, in prior art semiconductor laser diodes, light generation in the optical cavity leads to

drawbacks such as unfavorable internal reflection conditions for lateral propagation of optical modes and lower quality factors of vertical optical cavities with higher threshold currents. There is therefore a general need in the art for a light generation device that overcomes the aforementioned drawbacks in the prior art, and more particularly, a light generation device with an optical cavity (such as a VCSEL) that can operate with favorable internal reflection conditions for lateral propagation of optical modes and optimal quality factors of light generation in vertical optical cavities.

SUMMARY OF THE INVENTION

The invention provides a method and device for light generation wherein an embodiment of the device comprises a lower electrode, a conducting substrate formed on the lower electrode, and a triangle mesa structure having an optical cavity formed on the substrate. The triangle mesa structure (which can also be a truncated triangle mesa structure) further comprises an active layer, a lower conducting mirror and an upper conducting mirror for vertical confinement of light in the optical cavity, a contact layer formed on the upper mirror, a metallic contact formed on the contact layer. An electrical current is applied to the device according to the invention through the metallic contact linked to the contact layer, and subsequently to the lower electrode through the lower mirror and the conducting substrate. The applied current results in light generation in the active layer with vertical light output through the metallic contact.

With the method and device for light generation according to the invention, drawbacks in the prior art are advantageously overcome, and more particularly, light generation with favorable internal reflection conditions for lateral propagation of optical modes and optimal quality factors of light generation in vertical optical cavities.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages and features of the invention will become more apparent from the detailed description of the preferred embodiments of the invention given below with reference to the accompanying drawings, not necessarily drawn to scale, in which:

Fig. **1** is a diagram generally illustrating an embodiment of the light generation device having a triangle mesa structure according to the invention;

Fig. **2** is a diagram illustrating a further embodiment of the light generation device having a triangle mesa structure with a mirror sidewall reflector according to the invention;

Fig. **3** is a diagram illustrating an additional embodiment of the light generation device having a triangle mesa structure and a sidewall reflector with an optical grating according to the invention;

Fig. **4** is a diagram illustrating another embodiment of the light generation device having a triangle mesa structure according to the invention;

Fig. **5** is a diagram illustrating yet another embodiment of the light generation device having a triangle mesa structure according to the invention;

Fig. **6** is a diagram illustrating yet another embodiment of the light generation device having a triangle mesa structure according to the invention;

Fig. **7** is a diagram illustrating yet another embodiment of the light generation device having a triangle mesa structure according to the invention;

Fig. **8** is a diagram illustrating yet another embodiment of the light generation device having a triangle mesa structure according to the invention;

Fig. **9** is a diagram generally illustrating an exemplary active layer in the light generation device according to the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. **1** is a diagram that generally illustrates an embodiment of the light generation device having a triangle mesa structure according to the invention, i.e., a triangle vertical cavity surface emitting semiconductor laser (or T-VCSEL). According to this general embodiment of the invention, the T-VCSEL comprises a lower electrode **8**, a conducting substrate **9** and formed on the lower electrode **8**, and a triangle mesa structure **5** having an optical cavity **2** formed on the substrate **9**. The triangle mesa structure **5** (which can also be a truncated triangle mesa structure) further comprises an active layer **1**, a lower conducting mirror **4** and an upper conducting mirror **3** for vertical confinement of light in the optical cavity **2**, a contact layer **7** formed on the upper conducting mirror **3**, a metallic contact **6** formed on the contact layer **7**. An electrical current is applied to the T-VCSEL according to the invention through the metallic contact **6** linked to the contact layer **7**, and subsequently to the lower electrode **8** through the lower mirror **4** and the conducting substrate **9**. The applied current results in light generation in the active layer **1** with vertical light output in the direction **10** through the metallic contact **6**. As an electrical current is applied to the metallic contact **6**, light or laser is propagated through the triangle mesa structure **5**, and vertically output in the direction **10**, drawbacks in the prior art are advantageously overcome, and more particularly, light generation with favorable internal reflection conditions for lateral propagation of optical modes and optimal quality factors of light generation in vertical optical cavities.

The lower conducting mirror **4** can be made of, e.g., an n-type AlGaAs or InGaAsP or AlGaN semiconductor superlattice, and the upper

conducting mirror **3** accordingly made of a p-type AlGaAs or InGaAsP or AlGaN semiconductor superlattice, respectively. The upper and lower conducting mirrors can also be made of layered interference mirrors, layered metal-dielectric interference mirrors, layered dielectric-dielectric interference mirrors, or any interface between two dielectric structures with different refraction indices operating as a mirror for vertical confinement of light. Furthermore, the upper and lower mirrors can be made by etching, gluing or depositing of metal or dielectric material or plastic covered by metal lateral prism.

The active layer **1** can be made of a group III-V or II-VI semiconductor double heterostructure, a single quantum well (SQW), a multiple quantum well (MQW) or a current asymmetric resonance tunneling structure. Fig. **9** is a diagram that generally illustrates an exemplary active layer **1**, such as a current asymmetric resonance tunneling structure, used in the T-VCSEL according to the invention. The current asymmetric resonance tunneling structure comprises an n-contact **94**, a p-contact **95**, and two wells, namely a wide well **91** and an active quantum well **92**. The two wells **91** and **92** are coupled via a resonance tunneling barrier (RTB), which is transparent for electron transfer. The wide well **91** can be a single quantum well (SQW), i.e., a singular undoped electron emitting layer, or a multiple quantum well (MQW) as well. In a particular embodiment, an n-contact layer is deposited on top of a buffer layer formed on top of a substrate such as a sapphire or n-type GaAs substrate having a metallic contact. On the n-contact layer, an electron emitting wide well is epitaxially formed of an SQW or MQW structure. An SQW can be made of an undoped electron emitting layer made of, e.g., 0.02 μm to 0.2 μm thick $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.2 \le x \le 0.5$. An MQW can be made of, e.g., $(Al_xGa_{1-x})_{1-y}In_yP$ / $(Al_{x1}Ga_{1-x1})_{1-y1}In_{y1}P$ that is less than 1 μm thick, with $0.5 \le x \le 1$, $0.4 \le y \le 0.6$, $0 \le x1 \le 0.4$ and $0 \le y1 \le 0.4$. The RTB is then epitaxially deposited, which is made of an

undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer that is 10 Å (angstroms) to 100 Å thick, with $0.7 \leq x \leq 1$. The RTB allows resonant tunneling of the electrons from the wide well into the active quantum well, while blocking the hole tunneling from the active well into electron injection (or an electron injecting layer). A GaN layer is then deposited on top of the buffer layer to allow the current asymmetric resonance tunneling structure to be free standing after removal of the substrate by wet etching or laser ablation.

In this embodiment according to the invention as shown in Fig. **1** (which is discussed below in further detail), the substrate **9** is a conducting n-GaAs substrate with the light output by the T-VCSEL being generated with wavelength in the general region of 700 nm to 1300 nm. Furthermore, the triangle mesa structure **5** can also be a truncated triangle mesa structure. In a further variation of this particular embodiment (which is also discussed below in further detail), the substrate **9** can be a conducting n-InP substrate with the light output by the light generation device being generated with wavelength λ in the general region of 1300 nm to 1550 nm. According to an additional variation of this particular embodiment (which is also discussed below in further detail), the substrate **9** can be a conducting n-GaAs substrate with the light output by the T-VCSEL being generated with wavelength in the general region of 1300 nm.

According to this particular embodiment according to the invention where the substrate **9** is a conducting n-GaAs substrate and the light output by the T-VCSEL is generated with wavelength in the general region of 700 nm to 1300 nm, the triangle mesa structure **5** comprises a high-index GaAs optical cavity **2** having an active layer **1** made of InGaAs/GaAlAs double heterostructure, InGaAs/GaAlAs single quantum well, InGaAs/GaAlAs multiple quantum wells or a current asymmetric resonance tunnelling structure. Furthermore, the lower conducting mirror **4** is made of an n-type AlGaAs superlattice, whereas the upper conducting mirror **3** is

made of a p-type AlGaAs superlattice. The contact layer **7** is made of a p-type AlGaAs layer with a semitransparent metallic contact **6**.

According to a further variation of this particular embodiment according to the invention where the substrate **9** is a conducting n-InP substrate and the light output by the T-VCSEL is generated with wavelength in the general region of 1300 nm to 1550 nm, the triangle mesa structure **5** comprises a high-index InGaAsP or AlGaAsSb optical cavity **2** having an active layer **1** made of InGaAsP/InGaAsP double heterostructure, InGaAsP/InGaAsP single quantum well, InGaAsP/InGaAsP multiple quantum wells, or a current asymmetric resonance tunnelling structure. Furthermore, the lower conducting mirror **4** is made of an n-type InGaAsP/InGaAsP or AlGaPSb/AlGaPSb superlattice, whereas the upper conducting mirror **3** is made of a p-type InGaAsP/InGaAsP or AlGaPSb/AlGaPSb superlattice. The contact layer **7** is made of a p-type InP cladding layer with a semitransparent metallic contact **6**.

According to an additional variation of this particular embodiment according to the invention where the substrate **9** is a conducting n-GaAs substrate and the light output by the T-VCSEL is generated with wavelength in the general region of 1300 nm, the triangle mesa structure **5** comprises a high-index GaAs optical cavity **2** having an active layer **1** made of GaAsSb/GaAlAs double heterostructure, InGaAsN/GaAlAs double heterostructure, GaAsSb/GaAlAs single quantum well, InGaAsN/GaAlAs single quantum well, GaAsSb/GaAlAs multiple quantum wells, or InGaAsN/GaAlAs multiple quantum wells, or a current asymmetric resonance tunnelling structure. The lower conducting mirror **4** is made of an n-type AlGaAs superlattice, whereas the upper conducting mirror **3** is made of a p-type AlGaAs superlattice. The contact layer **7** is a p-type AlGaAs layer with a semitransparent metallic contact **6**.

Fig. **2** is a diagram that illustrates a further embodiment of the T-VCSEL with a mirror sidewall reflector **211** according to the invention. According to this particular embodiment of the invention, the T-VCSEL comprises a lower electrode **28**, a conducting substrate **29** and formed on the lower electrode **28**, and a triangle mesa structure **25** having an optical cavity **22** formed on the substrate **29**. The triangle mesa structure **25** (which can also be a truncated triangle mesa structure) further comprises an active layer **21**, a lower conducting mirror **24** and an upper conducting mirror **23** for vertical confinement of light in the optical cavity **22**, a contact layer **27** formed on the upper conducting mirror **23**, a metallic contact **26** formed on the contact layer **27**. This particular embodiment is similar in structure to the embodiment shown in Fig. **1**, except that a mirror sidewall reflector **211** is placed on the substrate **29** for deflecting the light generated from the active layer **21** and outputting the light in the direction **210**. As light or laser is applied to the T-VCSEL, the light is propagated through the active layer **21** and out to the mirror sidewall reflector **211** that deflects and outputs the light in the vertical direction **210**.

Fig. **3** is a diagram that illustrates an additional embodiment of the T-VCSEL with a sidewall reflector **311** with optical grating according to the invention. According to this particular embodiment of the invention, the T-VCSEL comprises a lower electrode **38**, a conducting substrate **39** and formed on the lower electrode **38**, and a triangle mesa structure **35** having an optical cavity **32** formed on the substrate **39**. The triangle mesa structure **35** (which can also be a truncated triangle mesa structure) further comprises an active layer **31**, a lower conducting mirror **34** and an upper conducting mirror **33** for vertical confinement of light in the optical cavity **32**, a contact layer **37** formed on the upper conducting mirror **33**, a metallic contact **36** formed on the contact layer **37**. This particular embodiment is similar in structure to the embodiment shown in Fig. **1**, except that a

sidewall reflector **311** with optical grating is placed on the substrate **39** for deflecting the light generated from the active layer **31** and outputting the light in output angles (including the output angle **310**) as divided or separated by the optical grating with respect to optical modes. As light or laser is applied to the T-VCSEL, the light is propagated through the active layer **31** and out to the sidewall reflector **311** that deflects and outputs the light in output angles (including the output angle **310**) as divided or separated by the optical grating with respect to optical modes.

Fig. **4** is a diagram that illustrates another embodiment of the triangle vertical cavity surface emitting semiconductor laser (or T-VCSEL) according to the invention. According to this particular embodiment of the invention, the T-VCSEL comprises a lower electrode **48**, a conducting substrate **49** and formed on the lower electrode **48**, and a triangle mesa structure **45** having an optical cavity **42** formed on the substrate **49**. The triangle mesa structure **45** (which can also be a truncated triangle mesa structure) further comprises an active layer **41**, a lower conducting mirror **44** and an upper conducting mirror **43** for vertical confinement of light in the optical cavity **42**, a cladding layer **412**, a contact layer **47** formed on the upper mirror **43**, a metallic contact **46** formed on the contact layer **47**. The lower conducting mirror **44** serves as an interface between the optical cavity **42** and the cladding layer **412**. The upper conducting mirror **43** serves as an interface between the optical cavity **42** and the contact layer **47**. The active layer **41** can be made of a group III-V or II-VI semiconductor double heterostructure, a single quantum well (SQW), a multiple quantum well (MQW) or a current asymmetric resonance tunneling structure, as discussed herein and above. An electrical current is applied to the T-VCSEL according to the invention through the metallic contact **46** linked to the contact layer **47**, and subsequently to the lower electrode **48** through the lower mirror **44** (linked to the cladding layer **412**) and the conducting substrate **49**. The

applied current results in light generation in the active layer **41** with vertical light output in the direction **410** through the metallic contact **46**. The light is propagated through the active layer **41** and out laterally to the sidewall reflector **411** that deflects and outputs the light in output angles (including the output angle **410**) as divided or separated by the optical grating with respect to optical modes.

In this embodiment according to the invention (which is discussed below in further detail), the substrate **49** is a conducting n-GaAs substrate with the light output by the T-VCSEL being generated with wavelength in the general region of 700 nm to 1000 nm. Furthermore, the triangle mesa structure **45** can also be a truncated triangle mesa structure. In a further variation of this particular embodiment (which is also discussed below in further detail), the substrate **49** can be a conducting n-InP substrate with the light output by the light generation device being generated with wavelength λ in the general region of 1300 nm to 1550 nm. According to an additional variation of this particular embodiment (which is also discussed below in further detail), the substrate **49** can be a conducting n-GaAs substrate with the light output by the T-VCSEL being generated with wavelength in the general region of 1300 nm.

According to this particular embodiment according to the invention where the substrate **49** is a conducting n-GaAs substrate and the light output by the T-VCSEL is generated with wavelength in the general region of 700 nm to 1000 nm, the triangle mesa structure **45** comprises a high-index AlGaAs optical cavity **42** having an active layer **41** made of InGaAs/GaAlAs double heterostructure, InGaAs/GaAlAs single quantum well, InGaAs/GaAlAs multiple quantum wells or a current asymmetric resonance tunnelling structure. Furthermore, the cladding layer **412** is made of an n-type AlGaAs cladding layer. The contact layer **47** is made of a p-type AlGaAs layer with a metallic contact **46**.

According to a further variation of this particular embodiment according to the invention where the substrate **49** is a conducting n-InP substrate and the light output by the T-VCSEL is generated with wavelength in the general region of 1300 nm to 1550 nm, the triangle mesa structure **45** comprises a high-index InGaAsP or AlGaAsSb optical cavity **42** having an active layer **41** made of InGaAsP/InGaAsP double heterostructure, InGaAsP/InGaAsP single quantum well, InGaAsP/InGaAsP multiple quantum wells, or a current asymmetric resonance tunnelling structure. Furthermore, the cladding layer **412** is made of an n-type AlGaInP cladding layer. The contact layer **47** is made of a p-type AlGaInP cladding layer with a metallic contact **46**.

According to an additional variation of this particular embodiment according to the invention where the substrate **49** is a conducting n-GaAs substrate and the light output by the T-VCSEL is generated with wavelength in the general region of 1300 nm, the triangle mesa structure **45** comprises a high-index AlGaAs optical cavity **42** having an active layer **41** made of GaAsSb/GaAlAs double heterostructure, InGaAsN/GaAlAs double heterostructure, GaAsSb/GaAlAs single quantum well, InGaAsN/GaAlAs single quantum well, GaAsSb/GaAlAs multiple quantum wells, or InGaAsN/GaAlAs multiple quantum wells, or a current asymmetric resonance tunnelling structure. Furthermore, the cladding layer **412** is made of an n-type AlGaAs cladding layer. The contact layer **47** is a p-type AlGaAs layer with a metallic contact **46**.

Fig. **5** is a diagram that illustrates yet another embodiment of the triangle vertical cavity surface emitting semiconductor laser (or T-VCSEL) according to the invention. The T-VCSEL shown in Figs. **6** and **7** is generally the same in structure, with minor exceptions in the manner by which light is output (e.g., a sidewall reflector **611** having an optical grating in Fig. **6** that deflects and outputs the light in output angles (including the output angle

610) as divided or separated by the optical grating with respect to optical modes), as the T-VCSEL shown in Fig. **5** (discussed in further detail below).

According to this particular embodiment of the invention, the T-VCSEL, which operates to generate light with wavelength in the general region of 400 nm to 700 nm, comprises a lower electrode **58**, a conducting n-GaN layer **59** formed on a sapphire substrate **512**, a BAlGaInN buffer layer **511**, a triangle or truncated triangle mesa structure **55**. The triangle mesa structure **55** further comprises a high-index InGaAlN optical cavity **52** having an active layer **51**, a lower conducting mirror **54** and an upper conducting mirror **53** for vertical confinement of light in the optical cavity **52**, a p-type InAlGaN contact layer **57**, and a semitransparent metallic contact **56**. The active layer **51** can be made of InGaN/InGaAlN double heterostructure, InGaN/InGaAlN single quantum well, InGaN/InGaAlN multiple quantum wells, or a current asymmetric resonance tunnelling structure. Furthermore, the lower conducting mirror **54** is made of an n-type AlGaN superlattice, whereas the upper conducting mirror **53** is made of a p-type AlGaN superlattice. An electrical current is applied to the T-VCSEL according to the invention through the semitransparent metallic contact **56** linked to the conducting mirror **53** through the contact layer **57** and the lower electrode **58** which is linked to the lower conducting mirror **54**, and through the conducting substrate **59**. The applied current results in light generation in active layer **51**, and vertical light output in the direction **510** through the semitransparent metallic contact **56**.

According to a further variation of this particular embodiment of the invention as shown in Fig. **5**, the T-VCSEL, which operates to generate light with wavelength in the general region of 400 nm to 700 nm, comprises a lower electrode **58** to a conducting n-SiC substrate **512**, a BAlGaInN buffer layer **511**, a conducting n-GaN layer **59**, and a triangle or truncated triangle mesa structure **55**. The triangle mesa structure **55** further

comprises a high-index InGaAIN optical cavity **52** having an active layer **51**, a lower conducting mirror **54** and an upper conducting mirror **53** for vertical confinement of light in the optical cavity **52**, a p-type InAlGaN contact layer **57**, and a semitransparent metallic contact **56**. The active layer **51** can be made of InGaN/InGaAIN double heterostructure, InGaN/InGaAIN single quantum well, InGaN/InGaAIN multiple quantum wells or a current asymmetric resonance tunnelling structure. Furthermore, the lower conducting mirror **54** is made of an n-type AlGaN superlattice, whereas the upper conducting mirror **53** is made of a p-type AlGaN superlattice. An electrical current is applied to the T-VCSEL according to the invention through the semitransparent metallic contact **56** linked to the conducting mirror **53** through the contact layer **57** and the lower electrode **58** which is linked to the lower conducting mirror **54**, and through the conducting substrate **59**. The applied current results in light generation in active layer **51**, and vertical light output in the direction **510** through the semitransparent metallic contact **56**.

Fig. **8** is a diagram that illustrates yet another embodiment of the triangle vertical cavity surface emitting semiconductor laser (or T-VCSEL) according to the invention. According to this particular embodiment of the invention, the T-VCSEL, which operates to generate light with wavelength in the general region of 400 nm to 700 nm, comprises a lower electrode **88**, a conducting n-GaN layer **89** formed on a sapphire substrate **814**, a BAlGaInN buffer layer **813**, and a triangle or truncated triangle mesa structure **85**. The triangle mesa structure **85** further comprises a high-index InGaAIN optical cavity **82** having an active layer **81**, an n-type AlGaN cladding layer **812**, a lower conducting mirror **84** and an upper conducting mirror **83** for vertical confinement of light in the optical cavity **52**, a p-type AlGaN contact layer **87**, and a metallic contact **86**. The active layer **81** can be made of InGaN/InGaAIN double heterostructure, InGaN/InGaAIN single quantum well,

InGaN/InGaAlN multiple quantum wells, or a current asymmetric resonance tunnelling structure. The lower conducting mirror **84** serves as an interface between the optical cavity **82** and the cladding layer **812**. The upper conducting mirror **83** serves as an interface between the optical cavity **82** and the contact layer **87**. An electrical current is applied to the T-VCSEL according to the invention through the metallic contact **86** linked to the contact layer **87**, and subsequently to the lower electrode **88** through the lower conducting mirror **84** (linked to the cladding layer **812**) and the substrate **814**. The applied current results in light generation in the active layer **81** with vertical light output in the direction **810** through the metallic contact **86**. The light is propagated through the active layer **81** and out laterally to the sidewall reflector **811** having an optical grating that deflects and outputs the light in output angles (including the output angle **810**) as divided or separated by the optical grating with respect to optical modes.

According to a further variation of this particular embodiment of the invention as shown in Fig. **8**, the T-VCSEL, which operates to generate light with wavelength in the general region of 400 nm to 700 nm, comprises a lower electrode **88** to a conducting n-SiC substrate **814**, a BAlGaInN buffer layer **813**, a conducting n-GaN layer **59**, and a triangle or truncated triangle mesa structure **85**. The triangle mesa structure **85** further comprises a high-index InGaAlN optical cavity **82** having an active layer **81**, an n-type AlGaN cladding layer **812**, a lower conducting mirror **84** and an upper conducting mirror **83** for vertical confinement of light in the optical cavity **82**, a p-type AlGaN contact layer **87**, and a metallic contact **86**. The active layer **81** can be made of InGaN/InGaAlN double heterostructure, InGaN/InGaAlN single quantum well, InGaN/InGaAlN multiple quantum wells or a current asymmetric resonance tunnelling structure. The lower conducting mirror **84** serves as an interface between the optical cavity **82** and the cladding layer **812**. The upper conducting mirror **83** serves as an interface between the

optical cavity **82** and the contact layer **87**. Similarly, an electrical current is applied to the T-VCSEL according to the invention through the metallic contact **86** linked to the contact layer **87**, and subsequently to the lower electrode **88** through the lower conducting mirror **84** (linked to the cladding layer **812**) and the substrate **814**. The applied current results in light generation in the active layer **81** with vertical light output in the direction **810** through the metallic contact **86**. The light is propagated through the active layer **81** and out laterally to the sidewall reflector **811** having an optical grating that deflects and outputs the light in output angles (including the output angle **810**) as divided or separated by the optical grating with respect to optical modes.

Although the invention has been particularly shown and described in detail with reference to the preferred embodiments thereof, the embodiments are not intended to be exhaustive or to limit the invention to the precise forms disclosed herein. It will be understood by those skilled in the art that many modifications in form and detail may be made without departing from the spirit and scope of the invention. Similarly, any process steps described herein may be interchangeable with other steps to achieve substantially the same result. All such modifications are intended to be encompassed within the scope of the invention, which is defined by the following claims and their equivalents.